

Pursuing the origin of electroweak symmetry breaking: a “Bayesian Physics” argument for a

$\sqrt{s} \lesssim 600 \text{ GeV } e^+e^-$ collider

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Abstract

High-energy data has been accumulating over the last ten years, and it should not be ignored when making decisions about the future experimental program. In particular, we argue that the electroweak data collected at LEP, SLC and Tevatron indicate a light scalar particle with mass less than 500 GeV. This result is based on considering a wide variety of theories including the Standard Model, supersymmetry, large extra dimensions, and composite models. We argue that a high luminosity, 600 GeV e^+e^- collider would then be the natural choice to feel confident about finding and studying states connected to electroweak symmetry breaking. We also argue from the data that worrying about resonances at multi-TeV energies as the only signal for electroweak symmetry breaking is not as important a discovery issue for the next generation of colliders. Such concerns should perhaps be replaced with more relevant discovery issues such as a Higgs boson that decays invisibly, and “new physics” that could conspire with a heavier Higgs boson to accommodate precision electroweak data. An e^+e^- collider with $\sqrt{s} \lesssim 600 \text{ GeV}$ is ideally suited to cover these possibilities.

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1 The many ideas of electroweak symmetry breaking

The mechanism of electroweak symmetry breaking (EWSB) is still mysterious. The “simplest” solution is to postulate the existence of one condensing $SU(2)$ doublet scalar field that gives masses to the vector bosons and the fermions. This idea is usually spoken of as the Standard Model explanation for electroweak symmetry breaking. However, the word “explanation” is perhaps too strong. The Higgs field provides no reason why it should have a vacuum expectation value, and it only exacerbates the hierarchy problem. Furthermore, the phase transition associated with the SM Higgs boson solution is not sufficiently strong first-order to explain the baryon asymmetry of the universe. These are just three of the reasons why the SM solution is unsatisfactory.

A long-standing endeavor in theoretical and experimental physics is going beyond the SM to explain EWSB at a more fundamental level. The would-be explanations (technicolor, top-quark condensation, supersymmetry, etc.) have invariably implied new particles and/or interactions with mass scale near the EWSB scale. For example, in strongly-coupled theories such as technicolor or top-quark condensation the new particles may include pseudo-Nambu-Goldstone bosons, and exotic gauge bosons (i.e., new forces) and fermions. In supersymmetry the new particles are superpartners and a second Higgs boson multiplet. In other words, one should expect additional particles correlated with a real explanation of EWSB beyond one

physical Higgs boson state.

The previous two paragraphs could have been written several years ago. What's new today is data. We sometimes bemoan the “lack of data” in high-energy physics. However, data has been coming in. Some theories have died as a result of the data, while other theories have been emerging as more viable and perhaps preferred by the data. This is what data is supposed to do. Data also should help us make decisions about what to look for in the future, and it should be one of the guiding principles to the future experimental program. This outlook we call “Bayesian Physics,” meaning that data and better understanding of theory is interpreted to suggest and imply future goals and experiments. Emphasis is placed on searching for theories or classes of theories that have experienced positive success when compared to data. The theories do not just survive, they have received positive support from the data. Supersymmetry is in this class, we believe.

A competitor philosophy is what we call “Nonjudgmental Physics.” In this philosophy, any physics idea (complete or incomplete) that still is technically not dramatically excluded by the data is equally likely. This outlook dictates, for example, that we view a light-Higgs predicting theory (supported by recent data) as equal in stature to a strong EWSB sector theory (not supported by recent data, and probably but not necessarily ruled out) when thinking about the requirements of future experiments. This philosophy is clearly the superior philosophy in the limit of infinite amount of time, money, and people to do experiments. We believe that the “Bayesian Physics” outlook can help set priorities when resources are limited, and may be essential to obtain new scientifically useful facilities.

2 Indications of a light Higgs boson

There are several important inputs from data that can help us decide what theories are more probable. Gauge coupling unification, for example, can be interpreted as a great success for supersymmetric theories. This alone may be powerful enough for some to consider only theories consistent with supersymmetry gauge coupling unification. Although we interpret gauge coupling unification as a powerful message that supersymmetry is part of nature, we will not dwell on this subject here. Instead, we wish to interpret the precision EW data in a wider class of theories.

We argue in this section that all theories that support a Higgs boson (composite or fundamental) with mass significantly less than about 500 GeV should be given special status over all other candidate theories of nature. Therefore, when making decisions about new collider facilities, it makes more sense to discuss and analyze all the vagaries of lower mass Higgs bosons than it does to compare a simple SM Higgs signature with signatures of a strongly coupled EWSB sector at very high energies. We will motivate this viewpoint in the next few paragraphs, and in the next sections we will outline some of the relevant discovery issues.

Since a strongly-coupled EWSB sector contributes to precision electroweak observables like a \sim TeV Higgs boson [1], it appears reasonable to declare these theories as less likely than other theories with fundamental or composite light Higgs bosons. Of course, it might be possible to construct a fully consistent theory that combines strongly coupled EWSB with other new physics that conspires to describe electroweak precision data. However, the new physics that accompanies such theories usually *worsens* the predictions for precision observables. For example, large positive contributions to the S parameter in technicolor theories combined with the effective high mass of a “Higgs boson” are incompatible with the data. In our view, strongly coupled EWSB, although not necessarily ruled out, has become a less-motivated concern given the current data. We will therefore not discuss further this possibility, and rather focus on the more data-motivated scenarios of light fundamental or composite Higgs bosons.

First, the EW precision data from LEP/SLD over the last ten years and direct searches for Higgs bosons at LEP2 indicate that a SM-like Higgs boson with mass between 110 GeV and 215 GeV is a good fit to the data (95% C.L.) [2]. This is our main input to the discussion. This lends support to any theory that predicts a SM-like Higgs boson with mass less than 215 GeV and above 110 GeV. Supersymmetry is one such theory; it certainly predicts $m_h < 215$ GeV, and a part of parameter space allows $m_h > 110$ GeV. Actually, the lightest physical Higgs boson of the general supersymmetry case can be as light as 85 GeV and consistent with LEP data. Also, there are no internal inconsistencies with the SM up to very high scales if its mass is in this range. In fact, if such a light SM-like Higgs boson can be taken at face value it may be possible to detect a Higgs boson at the Tevatron even before LHC and Tevatron [3].

A zeroth-order conclusion of a “Bayesian Physics” view of the data supporting a light

Higgs boson is to build a collider that can find and study a Higgs boson with mass less than 215 GeV. However, this may be a bit naive since the precision data is measuring virtual effects that may include cancellations and combinations of many different kinds of states that in the end imitate the effects of a light Higgs boson. In the next section we will discuss these possible conspiracies and show that they imply that the Higgs boson could be as heavy as 500 GeV, but not more.

3 Cancellation conspiracies for a heavy Higgs boson

The light Higgs boson requirements of precision EW data based on a SM analysis can be imitated by other effects. Several groups [4]–[12] have studied the possibility of raising the Higgs boson mass substantially above 215 GeV and using other states or operators to cancel the effects of this heavier Higgs mass in the radiative corrections, thereby allowing agreement with electroweak symmetry breaking.

One example of this type of conspiracy is found in ref. [5]. The theory is the SM in extra dimensions, where the fermions live on a 3+1 dimensional wall, and the gauge bosons live in a higher dimensional space [13, 14]. If the Higgs boson lives on the 3+1 dimensional wall with the SM fermions, it can mediate a mass mixing between the ordinary W, Z, γ gauge bosons and their Kaluza-Klein excitations. This mass mixing then leads to shifts in the EW precision observables that can mimic the effects of a light Higgs boson [5]. That is, a heavy Higgs boson plus gauge boson mode mixing leads to predictions for Z pole observables very similar to that of a light Higgs boson.

Any prediction for an observable \mathcal{O}_i (Γ_Z , $\sin^2 \theta_W^{\text{eff}}$, etc.) can be expanded approximately as

$$\mathcal{O}_i = \mathcal{O}_i^{\text{SM}} + a_i \log m_h/m_Z + b_i V. \quad (1)$$

$\mathcal{O}_i^{\text{SM}}$ is defined to be the best fit value of the observable assuming the SM and $m_h = m_Z$. We choose $m_h = m_Z$ arbitrarily for this expansion, but it is also convenient since it is approximately the value of m_h at the global minimum of the fitting χ^2 ,

$$\chi^2 = \sum_i \frac{(\mathcal{O}_i - \mathcal{O}_i^{\text{expt}})^2}{(\Delta \mathcal{O}_i^{\text{expt}})^2}. \quad (2)$$

V represents the effects on the observable from Kaluza-Klein excitations of the gauge bosons, and is defined as

$$V \equiv 2 \sum_{\vec{n}} \frac{g_{\vec{n}}^2}{g^2} \frac{m_W^2}{\vec{n}^2 M_c^2}, \quad (3)$$

where $M_c = R^{-1}$ is the compactification scale of the extra spatial dimension(s). If there is only one extra dimension then

$$V = \frac{\pi^2}{3} \frac{m_W^2}{M_c^2}. \quad (4)$$

The measurements of the observables $\mathcal{O}_i^{\text{expt}}$ are in good agreement with the SM prediction $\mathcal{O}_i^{\text{SM}}$ as long as $110 \text{ GeV} \lesssim m_h \gtrsim 215 \text{ GeV}$. If $b_i V = 0$ (decoupled effects of KK excitations) then \mathcal{O}_i is merely the prediction of the SM for some m_h . If m_h gets too large, \mathcal{O}_i gets further away from the best-fit value of $m_h \simeq m_Z$ and the prediction does not explain the data. However, if $b_i V \neq 0$, it is possible to have a cancellation between the $\log m_h/m_Z$ and V terms in Eq. (1) even for $m_h \gg m_Z$. This would constitute a “conspiracy” of cancellations to allow a large Higgs mass.

The trouble with conspiracies is that the cancellation must occur for *every* well-measured observable. Although cancellations can be arranged in some observables to maintain the light-Higgs SM prediction for larger Higgs mass and larger V , the cancellation cannot be maintained for all observables. The χ^2 function may stay under control for somewhat larger Higgs masses due to this cancellation adjustment among the most precisely measured observables, but at some point the less-precisely measured observables will deviate too far from the experimental measurements and cause the χ^2 to rise unacceptably high.

As an example of the general statements of the last few paragraphs, we show how the Higgs mass limit in extra dimensions can be increased above the SM limit but not to arbitrarily high values. The most precisely measured observable relevant to Higgs boson physics is $\sin^2 \theta_W^{\text{eff}}$. It can be expanded as

$$\sin^2 \theta_W^{\text{eff}} = \sin^2 \theta_W^{\text{eff,SM}} + 0.00053 \log m_h/m_Z - 0.44V. \quad (5)$$

Again, $\sin^2 \theta_W^{\text{eff,SM}}$ is the SM best-fit value for $m_h = m_Z$, which is in good agreement with the experimental measurement. To maintain this good agreement for higher Higgs mass, V must satisfy

$$V = 1.2 \times 10^{-3} \log m_h/m_Z. \quad (6)$$

For example, if $m_h = 500 \text{ GeV}$ then $V = 2.0 \times 10^{-3}$, which corresponds to a compactification scale of 3.3 TeV for one extra dimension. The compactification scale is also the mass of the first Kaluza-Klein excitations of the gauge bosons. Indeed the analysis of ref. [5] demonstrates this general relationship between m_h and V as derived in Eq. (6). However, $m_h = 500 \text{ GeV}$ is right at the edge of a tolerable *total* χ^2 for all precision observables. That is, the cancellation between large Higgs mass effects and Kaluza-Klein gauge boson effects is only partially working for other observables.

Another important observable is m_W . The theoretical prediction can be expanded similarly as we did for $\sin^2 \theta_W^{\text{eff}}$,

$$m_W = m_W^{\text{SM}} - (0.07 \text{ GeV}) \log m_h/m_Z + (34 \text{ GeV}) V. \quad (7)$$

Plugging in $m_h = 500 \text{ GeV}$ and $V = 0.002$ we get

$$m_W = m_W^{\text{SM}} - 0.12 \text{ GeV} + 0.07 \text{ GeV} = m_W^{\text{SM}} - 0.05 \text{ GeV}. \quad (8)$$

There is still a cancellation effect between heavy Higgs and light compactification scale in m_W , but it is not complete. The parameters have subtracted 50 MeV from the SM light-Higgs prediction. The measured value [2] and the SM best-fit prediction for m_W with $m_h = m_Z$ are

$$m_W^{\text{expt}} = 80.419 \pm 0.038 \text{ GeV} \quad \text{and} \quad m_W^{\text{SM}} = 80.395 \text{ GeV}. \quad (9)$$

Subtracting 50 MeV from m_W is clearly a prediction that does not match the measurement very well, and the large Higgs mass starts to run into trouble in the fit to EW parameters.

The above example is made more rigorous by doing a complete χ^2 analysis of the data using the parameters of the extra dimensional theory [5]. The result is that Higgs boson masses can be extended beyond the SM mass limit, but only up to 500 GeV at the 95% C.L. For $m_h > 500 \text{ GeV}$ the theory is not a good match to the data.

We believe that the extra-dimensional example illustrates a general lesson. That is, there are too many observables precisely measured to expect a global conspiracy cancellation between heavy Higgs effects (fundamental or composite) and other physics contributions. It may be possible to have a collection of higher-dimensional operators conspire to allow a larger Higgs mass [4, 7], but these examples are not real theories, and there appears to

be no motivation for choosing the considered effective Lagrangian other than to construct this cancellation. Furthermore, one can argue generally that these conspiracies of operator coefficients are unlikely [6, 11, 12].

Other specific example theories that demonstrate cancellation of the effects of a larger Higgs mass have been proposed in the literature [8]. One such theory is the see-saw top-quark condensate model [15, 16, 17], and the cancellation occurs between a heavy composite Higgs boson and the virtual effects of a massive quark mixing with the top quark [9]. However, as shown in [10], Higgs masses above 500 GeV are not allowed and still maintain theoretical consistency. Furthermore, ref. [10] has demonstrated an approximate 450 GeV mass limit on conspiring Higgs composite models. It is interesting that in all the more detailed, independent studies of conspiring theories such as the extra dimensional theory [5], and the composite theories [10], the mass limit of $m_h < 500$ GeV survives. And, of course, the minimal supersymmetric standard model automatically predicts a light SM Higgs boson. In all these cases, the indications from the data and a wide range of theory point to a Higgs mass below 500 GeV. We think this is the goal to shoot for in a high energy collider program.

4 Resolving the “new physics”

We have argued in the previous section that it is likely that a light Higgs boson exists and accounts for the precision EW data taken at the Z-pole and elsewhere. If its production and decay are close to that of the SM Higgs boson, both the NLC and the LHC could discover it. Nevertheless, the NLC would usher in an extraordinary era of precision Higgs boson physics, that would be useful in studying the dynamics and structure of EWSB symmetry breaking. To some, this is powerful enough reason to support an NLC program.

However, we would like to point out that there are important *discovery* issues surrounding a light Higgs boson. One issue that we will address in the next section is an invisibly decaying Higgs boson [18]. This possibility is certainly not a ridiculous theoretical musing, and we as a community should make sure that it is covered experimentally. The other discovery issue we would like to discuss is the “new physics” that conspires to allow a heavier Higgs boson satisfy the precision EW data. What is the most effective way to discover the nature of such new physics?

Above we gave two concrete examples of new physics that could conspire to allow a Higgs boson up to 500 GeV. One example is a top seesaw model with one $Y = 4/3$ fermion in addition to the SM fermions, and the other example is large extra dimensions for the gauge fields with the Higgs boson living on a $3 + 1$ dimensional wall with the fermions. We will consider each in turn.

First, we consider the top-quark seesaw model with one extra fermion with hypercharge $4/3$ as analyzed in ref. [9]. This fermion participates in a condensate seesaw with another quark to produce one light eigenvalue, the top quark t with mass $m_t \simeq 175$ GeV, and one heavy eigenvalue, χ . The effects of χ on precision EW analysis is such that it could conspire with a heavy composite Higgs boson to mimic the effects of a light Higgs boson. Actually, this statement is not precisely correct since varying the Higgs boson mass maps out a *different* path in the S - T plane, for example, than the path generated by varying the χ mass. S and T are defined [19] by

$$\frac{\Pi_{ZZ}(m_Z^2) - \Pi_{ZZ}(0)}{m_Z^2} = \frac{\alpha(m_Z)S}{\sin^2 2\theta_W(m_Z)} \quad (10)$$

$$\frac{\Pi_{WW}(0)}{m_W^2} - \frac{\Pi_{ZZ}(0)}{m_Z^2} = \alpha(m_Z)T \quad (11)$$

where all parameters are in the MS-bar scheme.

The SM prediction for S and T depends on m_t and m_h as well as other parameters of the theory. With the reference values $m_t^{\text{ref}} = 175$ GeV and $m_h^{\text{ref}} = 500$ GeV for the SM parameters we can calculate the prediction of S and T : $S_{\text{SM}}^{\text{ref}}$ and $T_{\text{SM}}^{\text{ref}}$. The experimental best fits to S and T are [7]

$$S_{\text{expt}} = S - S_{\text{SM}}^{\text{ref}} = -0.13 \pm 0.10 \quad (12)$$

$$T_{\text{expt}} = T - T_{\text{SM}}^{\text{ref}} = 0.13 \pm 0.11. \quad (13)$$

The 68% and 95% C.L. contours for this fit are given in Fig. 1. We have also put X marks on the plot for SM prediction with $m_h = 100$ GeV, 200 GeV, \dots , 1000 GeV going from left to right. As we can see from the plot, the 95% C.L. bound on the Higgs boson in the SM is between 200 GeV and 300 GeV, consistent with the value 229 GeV obtained in ref. [7].

The phenomenology of the one-doublet top seesaw model is very similar to the SM with one extra, massive quark χ . If light, this quark contributes substantially to T but very little

to S . Nevertheless, one could imagine a large Higgs mass conspiring with a smaller χ mass to generate a good fit to the data. We demonstrate an example of this by supposing that the Higgs boson has mass of $m_h = 500$ GeV and the χ has mass of about 5 TeV. Then, the shift in ΔT_χ can put the theory prediction well within the 95% C.L. contours of precision EW fits. This is the origin of the claim [9] that Higgs boson masses above 300 GeV are not in conflict with the data as long $5 \text{ TeV} \lesssim m_\chi \lesssim 7 \text{ TeV}$.

There are several lessons to learn from this example in our opinion. First, the Higgs mass in this theory is not expected to be above 500 GeV [10] in any event. We can understand this result by correlating the Higgs mass with the Landau pole scale Λ_{LP} where the Higgs self-coupling blows up. We plot Λ_{LP} vs. m_h in Fig. 2. The scale Λ_{LP} directly correlates with other parameters in the top seesaw model, most notably the extra fermion mass which must be below Λ_{LP} in order for condensation to occur. Therefore, knowing Λ_{LP} enables us to determine the effects of new physics on precision electroweak observables. As shown in [9, 10], the custodial symmetry violations associated with the new fermion mixing with the top quark induce a large contribution to the T parameter proportional to m_Z^2/m_χ^2 . The coefficient of this proportionality has been estimated, and a conservative conclusion is that no set of parameters with Higgs mass greater than 500 GeV will allow a good fit to precision electroweak data. In other words, as m_h gets higher Λ_{LP} gets lower, and as Λ_{LP} gets lower m_χ gets lower and causes T to be much too large to accomodate the precision electroweak data. We also note that from the discussion of limits on the coefficients of higher-dimensional operators (usually $\sim 1/(8 \text{ TeV})^2$ for dimension six operators [6]), it appears unlikely that conspiracies will be effective for any theory with a Higgs mass greater than 500 GeV.

The 500 GeV limit we have discussed for the top seesaw model is a specific case of the more general Chivukula-Simmons bound [20]. This bound states that when you correlate minimal custodial symmetry breaking requirements with the Higgs Landau pole scale, the experimentally measured bound on the T parameter imply stronger bounds on the Higgs boson than mere triviality. Note, this bound is not purely theoretical and requires the important input of precision electroweak data.

Nevertheless, a larger Higgs mass of up to 500 GeV can conspire to bring the prediction back into the allowed region in the S - T plane. However, this is not a *cancellation* of the effects of a large Higgs mass. The pathway made in the S - T plane by a variable Higgs mass

is significantly different than that made by varying other parts of the theory, in this case the χ mass. Better precision low-energy measurements would be able to distinguish the two theories. In the plot we anticipate a reduction of errors on $\sin^2 \theta_W^{\text{eff}}$ and Γ_Z by running on the Z pole with over 50 fb^{-1} of integrated luminosity at the NLC. Using ref. [21] as our guide, we think it might not be unreasonable to obtain $\Delta \sin^2 \theta_W^{\text{eff}} = 0.00002$ and $\Delta \Gamma_Z = 1 \text{ MeV}$ at the 95% C.L. The first estimate is well-within the anticipation of [21]; however, the second number is a factor of 4 better than cited by [21]. The error on $\sin^2 \theta_W^{\text{eff}}$ may be dominated by uncertainty in $\alpha_{\text{QED}}(m_Z)$. It is best reduced by doing precise scans of $e^+e^- \rightarrow \text{hadrons}$ at low energies, and a discussion of the experimental plans, expectations, and hopes can be found in ref. [22]. The error on m_Z is dominated by the uncertainty of \sqrt{s} and 1 MeV at the 95% C.L. may not be doable. Nevertheless, even with just the $\sin^2 \theta_W^{\text{eff}}$ measurement, one should be able to test consistency of a Higgs mass measurement with the predictions for S and T , and find a discrepancy, implying new states. The more precise measurement of $\Delta \Gamma_Z$ would help even more dramatically pin down the type of new physics that is compensating for the heavier Higgs boson. We also see from the graph, that the heavier the Higgs boson mass, the easier it should be to unravel any conspiracy with more Z -pole data. For this reason, we encourage additional study of the Z pole precision EW measurement capabilities at the NLC.

We also learn that although conspiracies do correlate with light “new physics” this does not guarantee that the new states will be directly produced and discovered at the next generation colliders. In the top seesaw model that we are considering now, neither the NLC nor the LHC will be able to directly observe $5 - 7 \text{ TeV}$ quarks. Only high-luminosity precision Z -pole measurements would really be able to see the evidence for new physics by constraining, for example, S and T to be off the Higgs boson path. With a precise measurement of the Higgs boson mass, the trajectory of the new physics in the S and T plane could be determined. We speak in terms of S and T here because it is valid and useful in this example, but in a more general approach one could analyze the multidimensional space of observables with all the self-energy and vertex corrections included.

The second example is large extra dimensions. We stated in the previous section that light Kaluza-Klein modes of the gauge bosons could conspire with a large Higgs mass to satisfy EW precision data. The global χ^2 implied that $m_h < 500 \text{ GeV}$ is required. If a

Higgs mass were discovered with mass somewhere between 400 GeV and 500 GeV, then one would expect in this scenario to find gauge boson KK states starting somewhere between 3.3 TeV and 6.6 TeV. This is clearly out of the reach for direct detection at the NLC, but the LHC will be able to see KK excitations up to at least 5.9 TeV with 100 fb⁻¹, covering a significant portion of the parameter space. On the surface this appears to be bad news for the NLC and good news for the LHC. However, the precision measurement capabilities of NLC at high energies allows one to be sensitive to virtual, tree-level exchanges of KK states in $e^+e^- \rightarrow Z^{(n)}/\gamma^{(n)} \rightarrow f\bar{f}$. The sensitivity to KK states using all the observables at one's disposal at the NLC is extraordinary. A 600 GeV NLC with 50 fb⁻¹ can see the effects of KK excitations well above 10 TeV [5]. Furthermore, one can show that the LHC will have an extremely difficult time resolving the degenerate KK modes from an “ordinary” Z' gauge boson. However, the NLC can resolve the difference [23].

Also, additional “new physics” discoveries might be possible only through production and subsequent decay of Higgs bosons. This could be the case if a Higgs boson decays into neutrinos or graviscalars in extra dimensions. Probably any decay mode of even the “heavier” Higgs bosons of conspiracy theories would still allow discovery. They are usually produced the traditional ways, in $Z/W + h$ associated production, $gg \rightarrow h$, and $WW \rightarrow h$. Below the top threshold they decay mainly to WW and ZZ and invisibly, and above the top threshold mainly to $t\bar{t}$ and possibly invisibly. At LHC they will be produced, but detecting them may be very difficult, particularly if the mass is above the top threshold. The invisibly decaying Higgs boson will be discussed in somewhat more detail in the next section. NLC has a significant advantage here.

In short, both theories discussed have been touted as explicit realizations of a conspiracy to accomodate a heavier Higgs boson in precision EW data. However, both theories upon close examination prefer the Higgs boson not be heavier than 500 GeV, kinematically accessible to a 600 GeV NLC. Furthermore, and perhaps most importantly, any new physics that contributes to the conspiracy is more likely to be discernible at the NLC than the LHC.

We have said very little about supersymmetry in this paper, even though we have more confidence in its relevance to nature than the other theories discussed. Supersymmetry has been well-established to predict a light-Higgs boson in the spectrum, easily accessible at the NLC. The “new physics” of supersymmetry are the superpartners. Unlike many other ideas,

supersymmetry is a well-defined, perturbative gauge theory, and it is possible to rationally study issues such as finetuning of electroweak symmetry breaking [24]. Numerous studies are in agreement that at least some superpartners should be less than a few hundred GeV. Furthermore, if the lightest supersymmetric partner is stable then cosmological constraints generally, but not always, imply upper bounds on superpartners accessible at the NLC [25, 26]. In our view it is rather obvious that supersymmetry enthusiasts would support the NLC, if for no other reason than to study the Higgs boson properties carefully. Our discussion above is meant for those who worry about a broader perspective.

5 Invisibly decaying Higgs boson is more pressing concern

In discussing the NLC capabilities of discovering and studying EWSB, one is often led to comparing with the LHC. The discussions usually begin with noting that kinematically accessible states will be studied very effectively at the NLC and decay branching fractions and production cross-sections will be measured to impressive accuracy. However, at this stage most of us are concerned with discovery, and so it is frequently brought up that the NLC will have a hard time with strongly coupled EWSB theories, where resonances at perhaps several TeV would be the only experimental indication that the $W_L W_L$ scattering cross-section is being unitarized. This has traditionally been implicitly thought of as the best example of a “problematic non-SM-like EWSB signal that must be covered”. The NLC typically struggles in this analysis.

However, we feel that the “metric” on all possible beyond-the-SM theories is grossly distorted by contrasting different collider’s ability to discover and study either a SM-like light Higgs boson or difficult multi-TeV resonance signals. There are many more *discovery* issues than strongly coupled EWSB sectors. And, from our discussion in the introduction and the previous section, we believe that the relevance of multi-TeV resonance signals has diminished dramatically given the data collected on the Z pole over the last ten years.

We would therefore like to emphasize other potential discovery issues for Higgs bosons. There are many possible discovery challenges for even light Higgs boson(s). Perhaps the most important “problematic non-SM-like EWSB signal that must be covered” is an invisibly

decaying Higgs boson. There are several well-motivated theoretical reasons [18] why a Higgs boson may preferentially decay into invisible, non-interacting states. These accessible decay modes certainly do not need to affect the Higgs couplings to gauge bosons or SM fermions, and so precision EW observable analyses would follow through just as for the SM Higgs boson. However, the decays will cause problems for the detectability of the Higgs boson itself. If we want to discover and study the Higgs bosons we should analyze carefully the prospects for discovering this rather difficult possibility. Similarly, the Higgs may decay invisibly only part of the time, which actually could make discovery more difficult at both NLC and LHC.

Furthermore, within the context of supersymmetry, there are many additional ways that Higgs boson *detectability* could be a major challenge to high-energy colliders. For example, a complex Higgs sector, with many physical light Higgs states may escape all detection at the LHC, and also be a challenge at the NLC. However, with sufficient luminosity, a 500 GeV NLC should be guaranteed to see a Higgs boson signal [27].

Returning to the single invisibly decaying Higgs case, there have been several analyses evaluating discovery possibilities at hadron colliders and lepton colliders. First, LEP II collaborations have published searches [28] for such states and generally get limits near $m_{h_{\text{inv}}} < 99 \text{ GeV}$ assuming SM strength coupling to the Z boson and 100% branching fraction into invisible final states. Future runs at LEP II will not go much beyond this number. Nevertheless, the limit is very close to the kinematic edge $\sqrt{s} - m_Z$ from $e^+e^- \rightarrow h_{\text{inv}}Z$. The Tevatron presently has no meaningful limits on the invisibly decaying Higgs boson. With over 30 fb^{-1} it may be possible to observe h_{inv} at the 3σ level if its mass is below $\sim 125 \text{ GeV}$ [29]. At the LHC, analyses indicate [30] that $m_{h_{\text{inv}}}$ may be probed up to $\sim 200 \text{ GeV}$ with 100 fb^{-1} . It would be worthwhile to redo the LHC analyses to take into account our current knowledge of SM particle properties (parton distributions, top quark mass, etc.) and the current expectations for detector parameters, such as particle identification, tagging and energy resolution.

An NLC analyses of the invisibly [31] decaying Higgs boson indicates that it can be probed very close to the kinematic limit of $\sqrt{s} - m_Z$. Again, this is the general expectation of the e^+e^- collider with a beam constraint to search for peaks in the missing invariant mass spectrum. We expect that shared branching fractions into invisible states and SM states will

be measured effectively at the NLC as well. Nevertheless, we encourage a detailed study on this important discovery issue, and think that a comparison between NLC and LHC for invisibly decaying Higgs boson searches is more appropriate than comparing capabilities for discovery of very large invariant mass resonances of strongly coupled EWSB.

6 Impact on future experiment: seeing through the many ideas

In summary, we have argued that a broad view of possible beyond-the-SM theories combined with the accumulated data of ten years at LEP and SLC indicate that we should expect a Higgs boson with mass less than 500 GeV. This presents many important discovery issues. The most notable of these issues is how to discover an invisibly decaying Higgs boson in this mass range. Other issues arise if the Higgs boson mass turns out to be at the upper end of this allowed range, having conspired with other “new physics” contributions to satisfy the current EW data. In both cases studied here, top seesaw model with an extra quark and large extra dimensions with KK gauge bosons at several TeV, the states are best resolved by precision measurements at the NLC running on the Z pole and at higher energy, $\sqrt{s} = 600$ GeV. Combining the results from these measurements it is possible to observe the heavier scalar and either the associated heavy quark or KK excitations of the gauge bosons. We think this result is probably general.

Finally, we emphasize what should be an obvious point to most: nothing is metaphysically certain. Certainty about what we may or may not find at the next collider has *never* been a part of the high-energy physics frontier. Our results are not theorems, but they are robust indications about what to bet on if one wants to pursue the most likely directions for progress in our field. If we knew what we were going to find there would be no reason to build colliders. Nevertheless, we think that the last decade of experimental physics is paying off and is providing us important clues that an NLC running at $\sqrt{s} \lesssim 600$ GeV will be rewarding. The NLC will vastly improve our chances of finding the origin of EWSB, and then would enable extraordinary precision EWSB measurements.

References

- [1] For a recent discussion of strongly coupled EWSB, see M. S. Chanowitz, “Strong W W scattering at the end of the 90’s: Theory and experimental prospects,” hep-ph/9812215.
- [2] The LEP Collaborations, “A combination of preliminary electroweak measurements and constraints on the Standard Model,” CERN-EP-2000-016 (January 21, 2000).
- [3] M. Carena, J. Lykken (coordinators), “Report of the Physics at Run II workshop on Supersymmetry and Higgs Physics,” To be published. Higgs results can be previewed at <http://fnth37.fnal.gov/higgs.html>.
- [4] L. Hall and C. Kolda, “Electroweak symmetry breaking and large extra dimensions,” Phys. Lett. **B459**, 213 (1999) [hep-ph/9904236].
- [5] T. G. Rizzo and J. D. Wells, “Electroweak precision measurements and collider probes of the standard model with large extra dimensions,” Phys. Rev. **D61**, 016007 (2000) [hep-ph/9906234]; A. Strumia, “Bounds on Kaluza-Klein excitations of the SM vector bosons from electroweak tests,” Phys. Lett. **B466**, 107 (1999) [hep-ph/9906266].
- [6] R. Barbieri and A. Strumia, “What is the limit on the Higgs mass?,” Phys. Lett. **B462**, 144 (1999) [hep-ph/9905281].
- [7] J. A. Bagger, A. F. Falk and M. Swartz, “Precision observables and electroweak theories,” hep-ph/9908327.
- [8] M.E. Peskin, J.D. Wells, in preparation.
- [9] H. Collins, A. Grant and H. Georgi, “The phenomenology of a top quark seesaw model,” Phys. Rev. **D61**, 055002 (2000) [hep-ph/9908330].
- [10] R. S. Chivukula, C. Holbling and N. Evans, “Limits on a composite Higgs boson,” hep-ph/0002022.
- [11] C. Kolda and H. Murayama, “The Higgs Mass and New Physics Scales in the Minimal Standard Model,” hep-ph/0003170.

- [12] W. J. Marciano, “Precision Electroweak Parameters and the Higgs Mass,” hep-ph/0003181.
- [13] I. Antoniadis, “A Possible New Dimension At A Few Tev,” Phys. Lett. **B246**, 377 (1990).
- [14] A. Pomarol and M. Quiros, “The standard model from extra dimensions,” Phys. Lett. **B438**, 255 (1998) [hep-ph/9806263].
- [15] B. A. Dobrescu and C. T. Hill, “Electroweak symmetry breaking via top condensation seesaw,” Phys. Rev. Lett. **81**, 2634 (1998) [hep-ph/9712319].
- [16] H. Cheng, B. A. Dobrescu and C. T. Hill, “Electroweak symmetry breaking and extra dimensions,” hep-ph/9912343.
- [17] R. S. Chivukula, B. A. Dobrescu, H. Georgi and C. T. Hill, “Top quark seesaw theory of electroweak symmetry breaking,” Phys. Rev. **D59**, 075003 (1999) [hep-ph/9809470].
- [18] Y. Chikashige, R. N. Mohapatra and R. D. Peccei, “Are There Real Goldstone Bosons Associated With Broken Lepton Number?,” Phys. Lett. **B98**, 265 (1981); R. E. Shrock and M. Suzuki, “Invisible Decays Of Higgs Bosons,” Phys. Lett. **B110**, 250 (1982); A. S. Joshipura and J. W. Valle, “Invisible Higgs decays and neutrino physics,” Nucl. Phys. **B397**, 105 (1993); R. S. Chivukula and M. Golden, “Hiding the electroweak symmetry breaking sector,” Phys. Lett. **B267**, 233 (1991); T. Binoth and J. J. van der Bij, “Influence of strongly coupled, hidden scalars on Higgs signals,” Z. Phys. **C75**, 17 (1997) [hep-ph/9608245]; N. Arkani-Hamed, S. Dimopoulos, G. Dvali and J. March-Russell, “Neutrino masses from large extra dimensions,” hep-ph/9811448; G. F. Giudice, R. Rattazzi and J. D. Wells, “Graviscalars from higher-dimensional metrics and curvature-Higgs mixing,” hep-ph/0002178.
- [19] M. E. Peskin and T. Takeuchi, “A New Constraint On A Strongly Interacting Higgs Sector,” Phys. Rev. Lett. **65**, 964 (1990); M. E. Peskin and T. Takeuchi, “Estimation of oblique electroweak corrections,” Phys. Rev. **D46**, 381 (1992).

- [20] R. S. Chivukula and E. H. Simmons, “Custodial symmetry and the triviality bound on the Higgs mass,” *Phys. Lett.* **B388**, 788 (1996) [hep-ph/9608320]; R. S. Chivukula and N. Evans, *Phys. Lett.* **B464**, 244 (1999) [hep-ph/9907414].
- [21] R. Hawkings and K. Monig, “Electroweak and CP violation physics at a linear collider Z-factory,” hep-ex/9910022.
- [22] Z. Zhao, “R-values in low energy $e^+ e^-$ annihilation,” hep-ex/0002025.
- [23] T. G. Rizzo, “Testing the nature of Kaluza-Klein excitations at future lepton colliders,” *Phys. Rev.* **D61**, 055005 (2000) [hep-ph/9909232].
- [24] R. Barbieri and G. F. Giudice, “Upper Bounds On Supersymmetric Particle Masses,” *Nucl. Phys.* **B306**, 63 (1988); G. W. Anderson and D. J. Castano, “Challenging weak scale supersymmetry at colliders,” *Phys. Rev.* **D53**, 2403 (1996) [hep-ph/9509212]; M. Bastero-Gil, G. L. Kane and S. F. King, “Fine-tuning constraints on supergravity models,” *Phys. Lett.* **B474**, 103 (2000) [hep-ph/9910506].
- [25] G. L. Kane, C. Kolda, L. Roszkowski and J. D. Wells, “Study of constrained minimal supersymmetry,” *Phys. Rev.* **D49**, 6173 (1994) [hep-ph/9312272]; J. D. Wells, “Supersymmetric dark matter with a cosmological constant,” *Phys. Lett.* **B443**, 196 (1998) [hep-ph/9809504]. Some potential exceptions are given in M. Drees and M. M. Nojiri, “The Neutralino relic density in minimal $N=1$ supergravity,” *Phys. Rev.* **D47**, 376 (1993) [hep-ph/9207234];
- [26] J. Ellis, T. Falk and K. A. Olive, “Neutralino stau coannihilation and the cosmological upper limit on the mass of the lightest supersymmetric particle,” *Phys. Lett.* **B444**, 367 (1998) [hep-ph/9810360]; C. Boehm, A. Djouadi and M. Drees, “Light scalar top quarks and supersymmetric dark matter,” hep-ph/9911496; J. Ellis, G. Ganis and K. A. Olive, “Supersymmetric dark matter and the energy of a linear electron positron collider,” *Phys. Lett.* **B474**, 314 (2000) [hep-ph/9912324].
- [27] J. R. Espinosa and J. F. Gunion, “A no-lose theorem for Higgs searches at a future linear collider,” *Phys. Rev. Lett.* **82**, 1084 (1999) [hep-ph/9807275].

- [28] P. Abreu *et al.* [DELPHI Collaboration], “A search for invisible Higgs bosons produced in e^+e^- interactions at LEP2 energies,” Phys. Lett. **B459**, 367 (1999); L3 Collaboration, “Missing mass spectra in leptonic and hadronic events from e^+e^- collisions at $\sqrt{s} = 189$ GeV and limits on invisible Higgs decays,” Submitted to *International Europhysics Conference High Energy Physics 99* Tampere, Finland, 15-21 July 1999 (L3 Note 2435); R. Barate *et al.* [ALEPH Collaboration], “Search for an invisibly decaying Higgs boson in e^+e^- collisions at 189-GeV,” Phys. Lett. **B466**, 50 (1999); OPAL Collaboration, “Search for invisibly decaying Higgs bosons in Z^0h^0 production at $\sqrt{s} = 183$ and 189 GeV,” Submitted to *International Europhysics Conference High Energy Physics 99* Tampere, Finland, 15-21 July 1999 (OPAL PN399).
- [29] S. P. Martin and J. D. Wells, “Motivation and detectability of an invisibly-decaying Higgs boson at the Fermilab Tevatron,” Phys. Rev. **D60**, 035006 (1999) [hep-ph/9903259].
- [30] S. G. Frederiksen, N. Johnson, G. Kane and J. Reid, “Detecting invisible Higgs bosons at the CERN Large Hadron Collider,” Phys. Rev. **D50**, 4244 (1994); J. F. Gunion, “Detecting an invisibly decaying Higgs boson at a hadron supercollider,” Phys. Rev. Lett. **72**, 199 (1994) [hep-ph/9309216]; D. Choudhury and D. P. Roy, “Signatures of an invisibly decaying Higgs particle at LHC,” Phys. Lett. **B322**, 368 (1994) [hep-ph/9312347].
- [31] O. J. Eboli, M. C. Gonzalez-Garcia, A. Lopez-Fernandez, S. F. Novaes and J. W. Valle, “Searching for an invisibly decaying Higgs boson in e^+e^- , e gamma and gamma gamma collisions,” Nucl. Phys. **B421**, 65 (1994) [hep-ph/9312278].

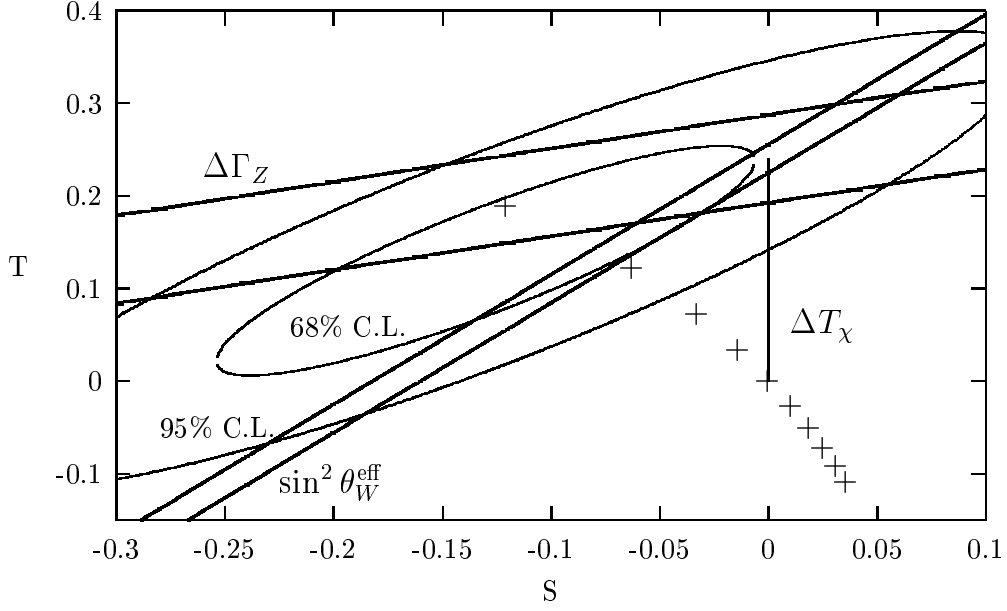


Figure 1: Best fit values to S and T relative to the SM reference point with $m_t = 175$ GeV and $m_h = 500$ GeV. The larger circles represent current constraints as calculated by [7]. The X marks on the graph refer to Higgs boson masses 100 GeV, 200 GeV, ..., 1000 GeV from left to right. The vertical line labelled ΔT_χ represents a $m_\chi \simeq 5$ TeV new quark conspiring with $m_h = 500$ GeV for an acceptable fit to the current data. The steeper narrow strip illustrates the 95% C.L. band allowed by a measurement of $\Delta \sin^2 \theta = 0.00004$ (95% C.L.), and the less steep strip illustrates the 95% C.L. band allowed by a measurement of $\Delta \Gamma_Z = 1$ MeV (95% C.L.). These values may be obtained at the NLC if more than about 50 fb^{-1} is obtained on the Z pole.

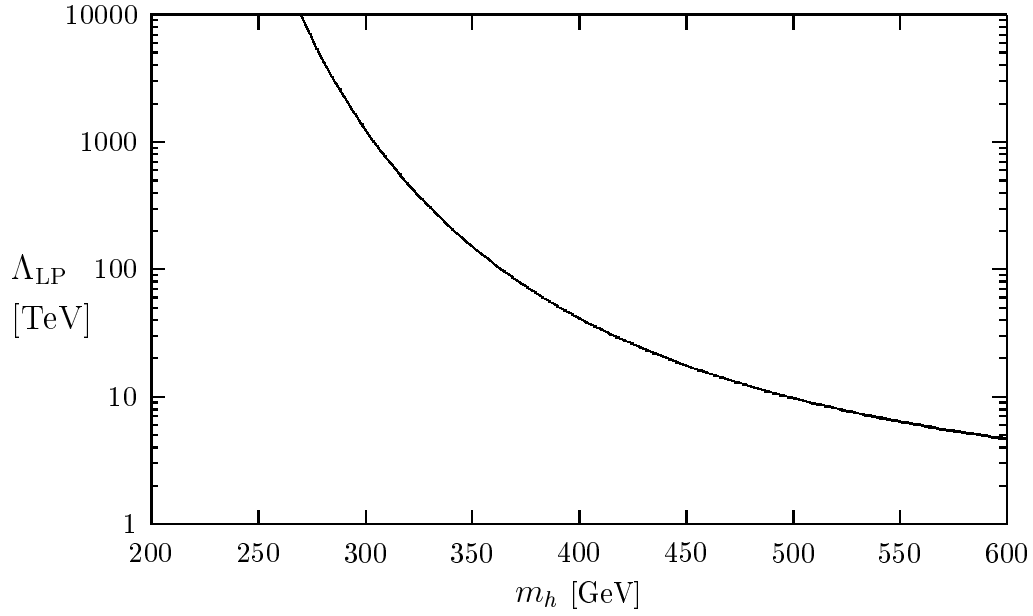


Figure 2: Λ_{LP} is the scale at which the Higgs boson self-coupling reaches its Landau pole (blows up). It is correlated with higher dimensional operators that can alter the predictions for precision electroweak observables. As m_h goes higher, Λ_{LP} gets lower and runs an increasing risk of disrupting good agreement with the data. For $m_h \geq 500$ GeV, $\Lambda_{\text{LP}} \lesssim$ several TeV which generally implies too large corrections to EW observables.